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# Prediction of reinjection effects in fault-related subsidiary structures by using fractional derivative-based mathematical models for sustainable design of geothermal reservoirs

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ABSTRACT

This study provides a method to evaluate the effects of cold-water injection into an advection-dominated geothermal reservoir. A fractional advection-dispersion equation (fADE) and a fractional heat transfer equation (fHTE) are applied to fault-related structures in geothermal areas where the fracture density is described by a power-law model. Synthetic production data generated by a numerical reservoir simulator reveal that the fADE and the fHTE are in reasonable agreement with the tracer responses and temperature change in a fault zone. Tracer analysis based on the fADE has potential to elucidate fault-related structures and to predict premature thermal breakthroughs quickly and efficiently.

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## 1. Introduction

Geothermal energy is a promising energy source for stable generation of electricity regardless of the weather or time of day. Most geothermal power plants extend the lifespan of the resources by sustaining the amount of water and pressure within the reservoir. Reinjection is of great importance for sustainable utilization of geothermal systems, which has been discussed in Axelsson (2010) and Kaya et al. (2011). One of the major problems with this reinjection process, however, is the possibility of an early thermal breakthrough in production areas. There remains a need to establish criteria and guidelines for sustainable reinjection operations that allow us to design the location of wells, injection temperatures, and/or flow rates.

Fracture and fracture networks contribute critically to fluid flow and heat propagation. In a geothermal reservoir, structures associated with large-scale faults appear to be quite important in controlling fluid flow (Massart et al., 2010). The simplest description of a fault zone structure (and fault zones in general) considers two major mechanical units, namely a fault core and a damage zone (cf., Caine et al., 1996; Faulkner et al., 2010). The fault core is formed through repeated slipping of the principal fault plane and is composed of impermeable barriers. The damage zone consists of a volume of deformed rocks with smaller fractures around a fault surface that results from slips along faults (Caine et al., 1996). In the fault damage zone, the fracture density (the number of fractures per unit length) commonly increases near the fault core (e.g., Brock and Engelder, 1977; Chester and Logan, 1986; Agosta and Kirschner, 2003; De Joussineau and Aydin, 2007; Gudmundsson, 2011). Savage and Brodsky (2011) found that isolated single faults with small displacements have macrofracture densities that decay as a power law. The power-law function is a feature of fractal geometry, which provides widely applicable and descriptive tools for characterization of subsurface fracture systems (Bonnet et al., 2001).

Tracer testing is a standard method for evaluating fluid flow within a geothermal reservoir. Tracer responses often observed in geothermal fields include non-Gaussian leading or trailing edges (also called heavy tails) of a plume emanating from a point source, or nonlinear growth of the centered second moment (e.g., Sanjuan et al., 2006). Numerous numerical experiments indicate that anomalous dispersion cannot be described by the traditional second-order advection-dispersion equation (ADE) that is based

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